Dark Matter and Electroweak Baryogenesis

Rencontres de Moriond: Electroweak Interactions and Unified Theories

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Open questions in the Standard Model

- Source of Mass of fundamental particles.

- Origin of the observed asymmetry between particles and antiparticles (Baryon Asymmetry).

- Nature of the Dark Matter, contributing to most of the matter energy of the Universe.

- Quantum Gravity and Unified Interactions.

Evidence for Dark Matter:

Visible stars do not account for enough mass to explain the rotation curves of galaxies

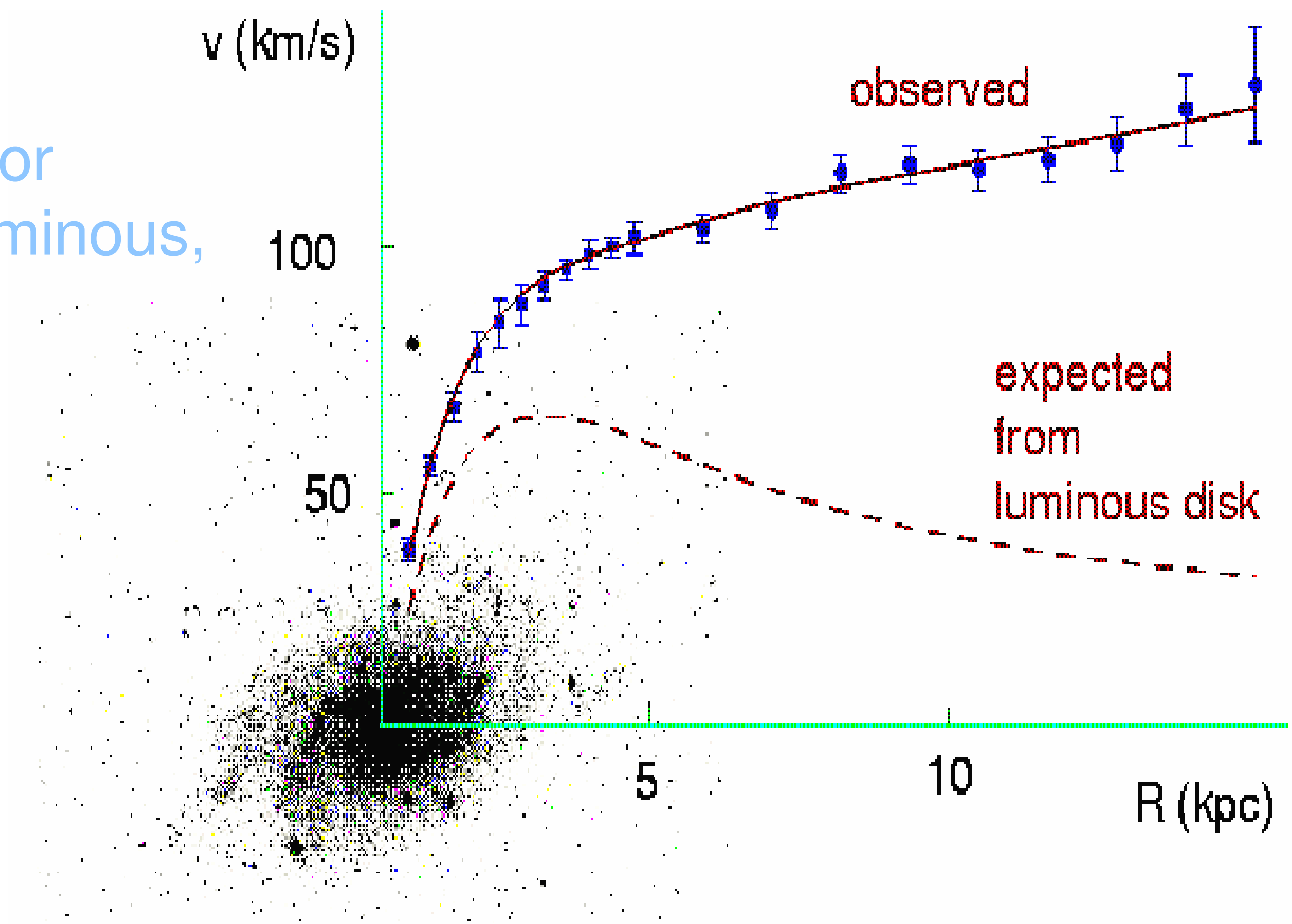
Gravity prediction: $$\frac{v^2}{r} = G_N \frac{M(r)}{r^2} \Rightarrow v^2 \propto \frac{1}{r}$$

Strong evidence for additional, non-luminous, source of matter:

$\Downarrow$

Dark Matter

Zwicky , 1930s



Cosmic Microwave Background

WMAP measures the CMB and determines

$\Omega_M h^2 = 0.135 \pm 0.009$ $\Omega_B h^2 = 0.0224 \pm 0.0009$ $h = 0.71 \pm 0.04$

difference gives CDM energy density: $\Omega_{\mathrm{CDM}}\, h^2 = 0.1126 \pm^{0.0161}_{0.0181}$

Possible origin of Dark Matter

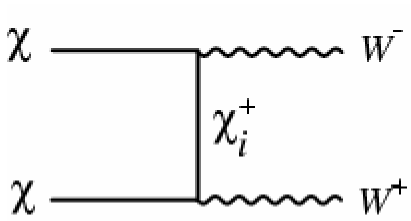
- Weakly interacting particles (WIMPS), with masses and interaction cross sections of order of the electroweak scale

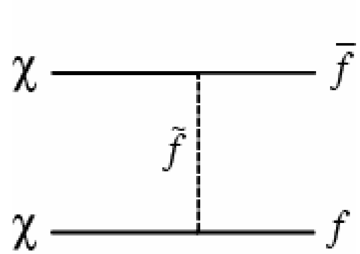
  $\longrightarrow$ most compelling alternative

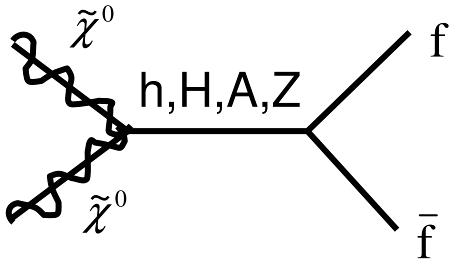
- Supersymmetry, with R parity conservation

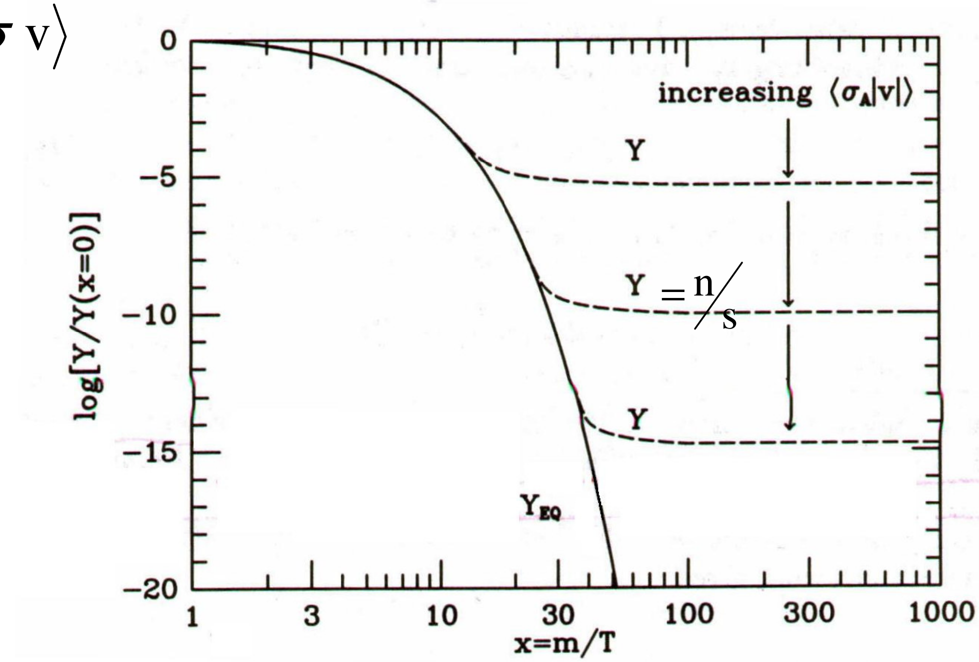
naturally provides a stable, neutral, dark matter candidate: $\tilde{\chi}^0$

Relic density is inversely proportional to the thermally averaged $\tilde{\chi}^0\tilde{\chi}^0$ annihilation cross section $\langle \sigma\, v \rangle$

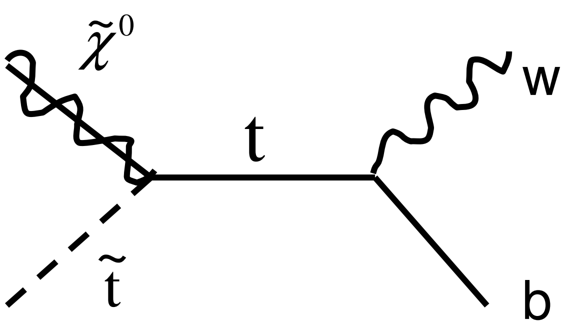


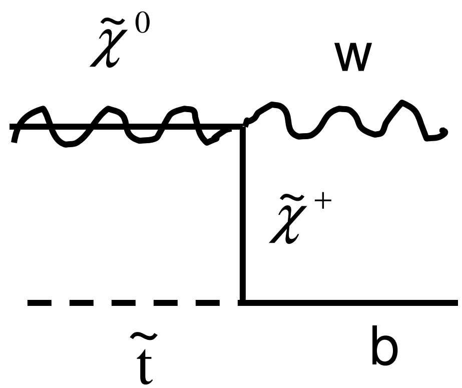






If any other SUSY particle has mass close to the neutralino LSP, it may substantially affect the relic density via co-annihilation





if stops NLSP

neutralino-stop

co-annihilation

The Puzzle of the Matter-Antimatter asymmetry

- Anti-matter is governed by the same interactions as matter.
- Observable Universe is mostly made of matter: $N_B >> N_{\overline{B}}$
- Anti-matter only seen in cosmic rays and particle physics accelerators
  The rate observed in cosmic rays consistent with secondary emission of antiprotons $N_{\overline{P}} \approx 10^{-4} \; N_P$

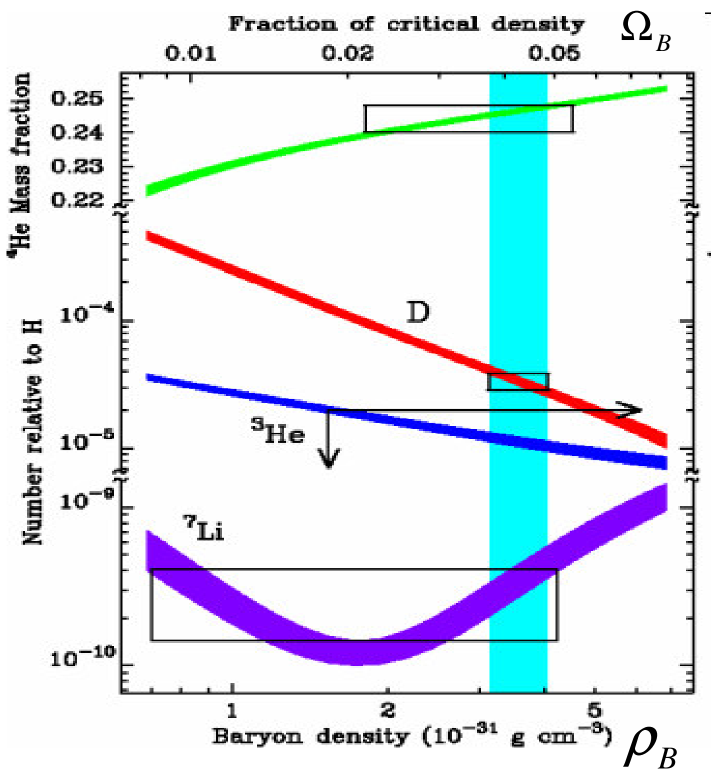
Information on the baryon abundance:

- Abundance of primordial elements combined with predictions from Big Bang Nucleosynthesis:

$$\eta = \frac{n_B}{n_\gamma}, \quad n_\gamma = \frac{421}{cm^3}$$

- CMBR:

$$\frac{\rho_B}{\rho_c} \equiv \Omega_B, \qquad \rho_c \approx 10^{-5} h^2 \frac{GeV}{cm^3}$$



Baryon-Antibaryon asymmetry

- Baryon Number abundance is only a tiny fraction of other relativistic species

$$\eta = \frac{n_B}{n_\gamma} = 2.68\ 10^{-8}\,\Omega_B h^2 \approx 6\ 10^{-10}$$

- In early universe $\mathrm{B}, \overline{\mathrm{B}}$ and γ's were equally abundant. $\mathrm{B}, \overline{\mathrm{B}}$ annihilated very efficiently. No net baryon number if B would be conserved at all times. What generated the small observed baryon antibaryon asymmetry ?

Sakharov's Requirements:

- Baryon Number Violation (any B conserving process: $N_B = N_{\overline{B}}$)
- C and CP Violation: $(N_B)_{\mathrm{L,R}} \neq (N_{\overline{B}})_{L,R}$
- Departure from thermal equilibrium

All three requirements fulfilled in the SM

In the SM Baryon Number conserved at classical level but violated at quantum level : $\Delta B = \Delta L$

Anomalous processes violate both B and L number, but preserve B-L. (Important for leptogenesis idea)

- ***At T = 0, Baryon number violating processes exponentially suppressed***

$$\Gamma_{\Delta B \neq 0} \cong \exp(-2\pi / \alpha_{\mathrm{W}})$$

- ***At very high temperatures they are highly unsuppressed,***

$$\Gamma_{\Delta B \neq 0} \propto T$$

- ***At Finite Temperature, instead, only Boltzman suppressed***

$$\Gamma_{\Delta B \neq 0} \cong \beta_0 \, \mathrm{T} \exp(-\mathrm{E}_{\mathrm{sph}}(\mathrm{T}) / \mathrm{T})$$

with $\mathrm{E}_{\mathrm{sph}} \cong 8\pi\, \mathrm{v(T)} / \mathrm{g}$ and v(T) the Higgs v.e.v.

Baryogenesis at the Electroweak Phase transition

- Start with B=L=0 at T>Tc

- CP violating phases create chiral baryon-antibaryon asymmetry in the symmetric phase. Sphaleron processes create net baryon asymmetry.

- Net Baryon Number diffuse in the broken phase

if $n_{\mathbf{B}} = 0$ at T > Tc, independently of the source of baryon asymmetry

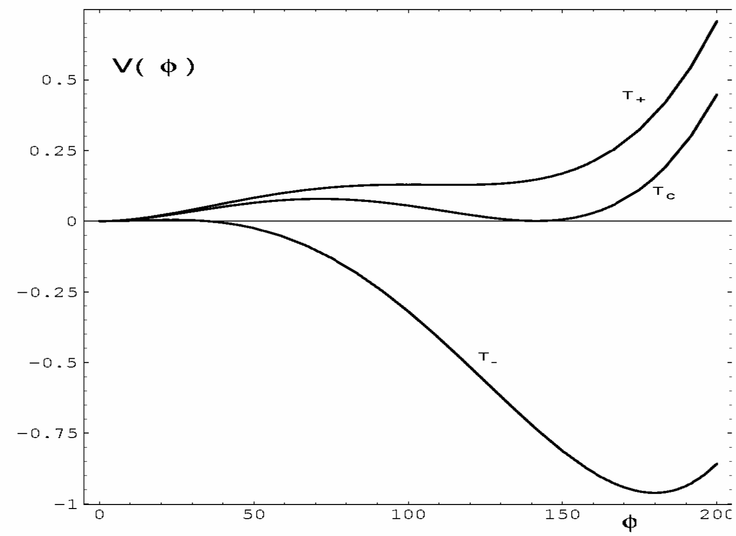
$$\frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp\left(-\frac{10^{16}}{\mathrm{T_c(GeV)}} \exp\left(-\frac{\mathrm{E_{sph}(T_c)}}{\mathrm{T_c}}\right)\right)$$

To preserve the generated baryon asymmetry:

strong first order phase transiton:

$$v(T_c)/T_c > 1$$

Baryon number violating processes out of equilibrium in the broken phase



SM Electroweak Baryogenesis fufills the Sakharov conditions

- **SM Baryon number violation: Anomalous Processes**
- **CP violation: Quark CKM mixing**
- **Non-equilibrium: Possible at the electroweak phase transition.**

Finite Temperature Higgs Potential

$$V = D(T^2 - T_0^2) H^2 + E T \; H^3 + \lambda \; H^4$$

E receives contributions proportional to the sum of the cube of all light boson particle couplings

$$\frac{v(T_c)}{T_c} \approx \frac{E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2}$$

Since in the SM the only bosons are the gauge bosons, and the quartic coupling is proportional to the square of the Higgs mass

$$\frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H < 40 \text{ GeV} \Rightarrow \text{ ruled out!}$$

- **Independent Problem: not enough CP violation**

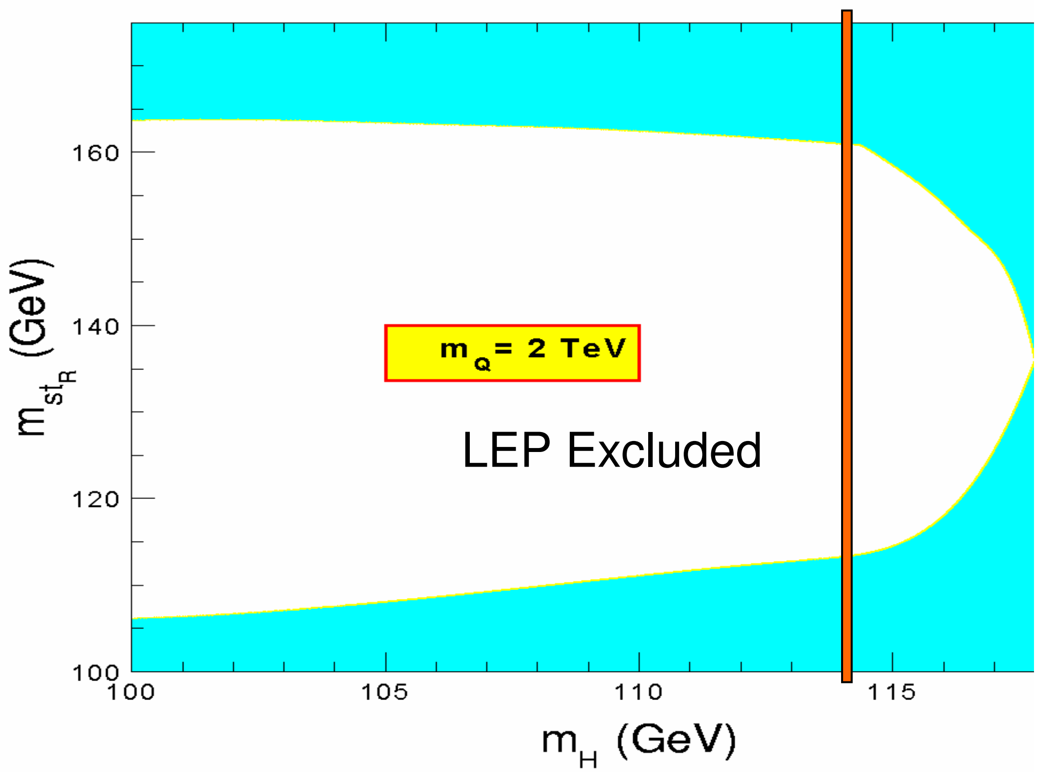
Electroweak Baryogenesis in the SM is ruled out

In the MSSM:

- New bosonic degrees of freedom: superpartners of the top quark, with strong couplings to the Higgs. $\Rightarrow E_{SUSY} \approx 8\, E_{SM}$

Suficciently strong first order phase transition to preserve generated baryon asymmetry:

- ***Higgs masses up to 120 GeV***
- ***The lightest stop must have a mass below the top quark mass.***



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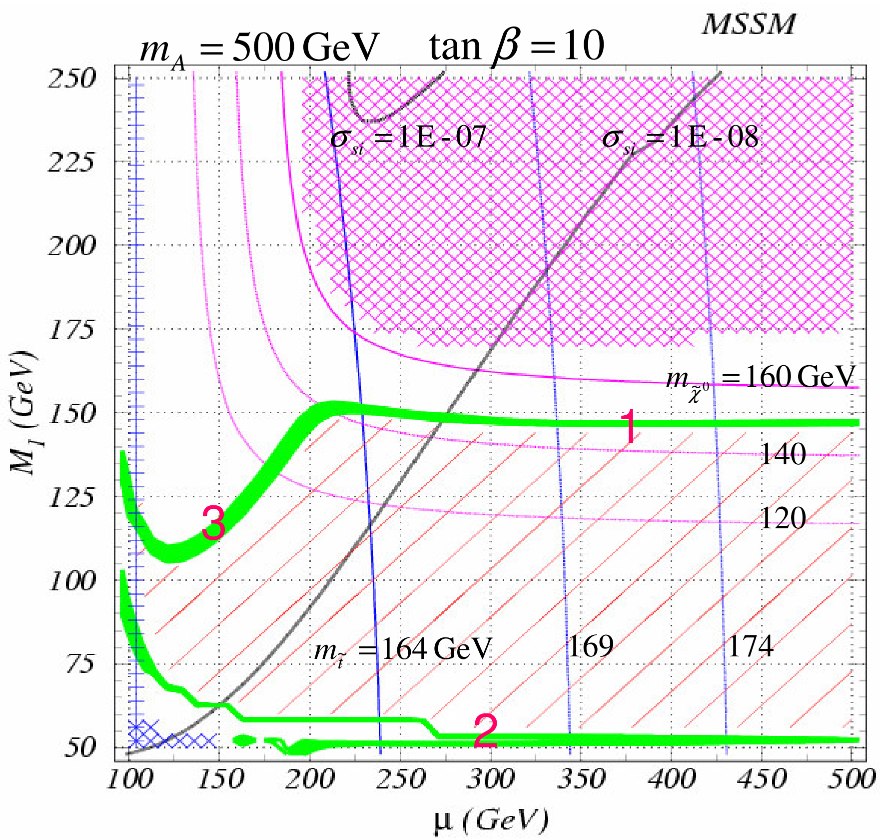
Dark Matter and Electroweak Baryogenesis

• light right handed stop: $m_{\tilde{U}_3} \approx 0$ • heavy left handed stop: $m_{\tilde{Q}_3} \geq 1\,\mathrm{TeV}$

• values of stop mixing compatible with Higgs mass constraints and with a strong first order phase transition: $X_t = \mu / \tan\beta - A_t = 0.3 - 0.5\,\mathrm{m}_{\tilde{Q}_3}$

• the rest of the squarks, sleptons and gluinos order TeV and $\mathrm{M}_2 \cong 2\mathrm{M}_1$



three interesting regions with neutralino relic density compatible with WMAP obs.

$0.095 < \Omega_{\mathrm{CDM}} h^2 < 0.129$ (green areas)

1. neutralino-stop co-annihilation: mass difference about 20-30 GeV

2. s-channel neutralino annihilation via lightest CP-even Higgs

3. annihilation via Z boson exchange

small μ and M_1

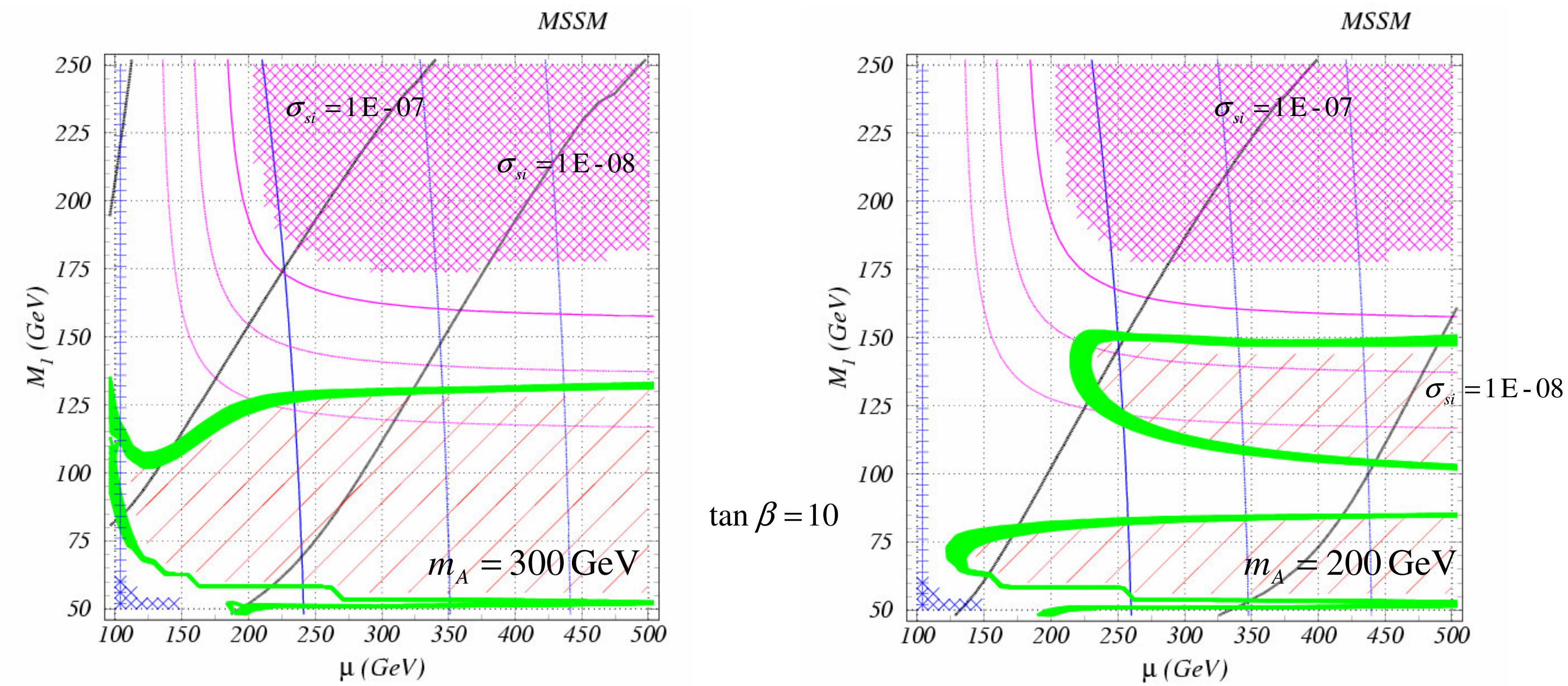
Balazs, MC, Wagner 04

Heavy Higgs mass Effects

A,H contribute to annihilation cross section vis s-channel:

- $m_A = 300\,\mathrm{GeV}$ main effect for values of neutralino mass close to stop mass, allowed region moves away from co-annihilation to lower neutralino masses

- $m_A = 200\,\mathrm{GeV}$ new resonant region due to A,H s-channel (much wider band than for h due to $\tan\beta$ enhanced bb couplings). Stop co-annihilation region reappears.



- larger neutralino-proton scattering cross sections!

Balazs, MC, Wagner

Experimental Tests of
Electroweak Baryogenesis and Dark Matter

- Higgs searches:

Higgs associated with electroweak symmetry breaking: SM-like.
Higgs mass below 120 GeV required

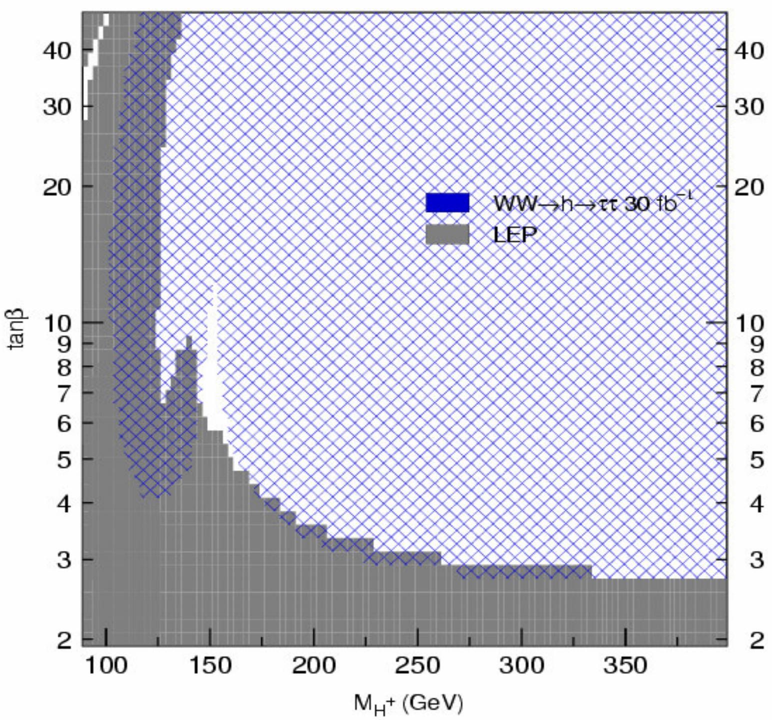
1. Tevatron collider may test this possibility: 3 sigma evidence with about 4 fb^{-1}

Discovery quite challenging, detecting a signal will mean that the Higgs has relevant strong (SM-like) couplings to W and Z

2. A definitive test of this scenario will come at the LHC with the first 30 fb^{-1} of data

$$qq \rightarrow qqV^*V^* \rightarrow qqh$$
$$\text{with } h \rightarrow \tau^+\tau^-$$

Maximal mixing scenario



Searches for a light stop at the Tevatron

Light-stop models with neutralino LSP dark matter $\longrightarrow$ $\not{E}_T$ signal

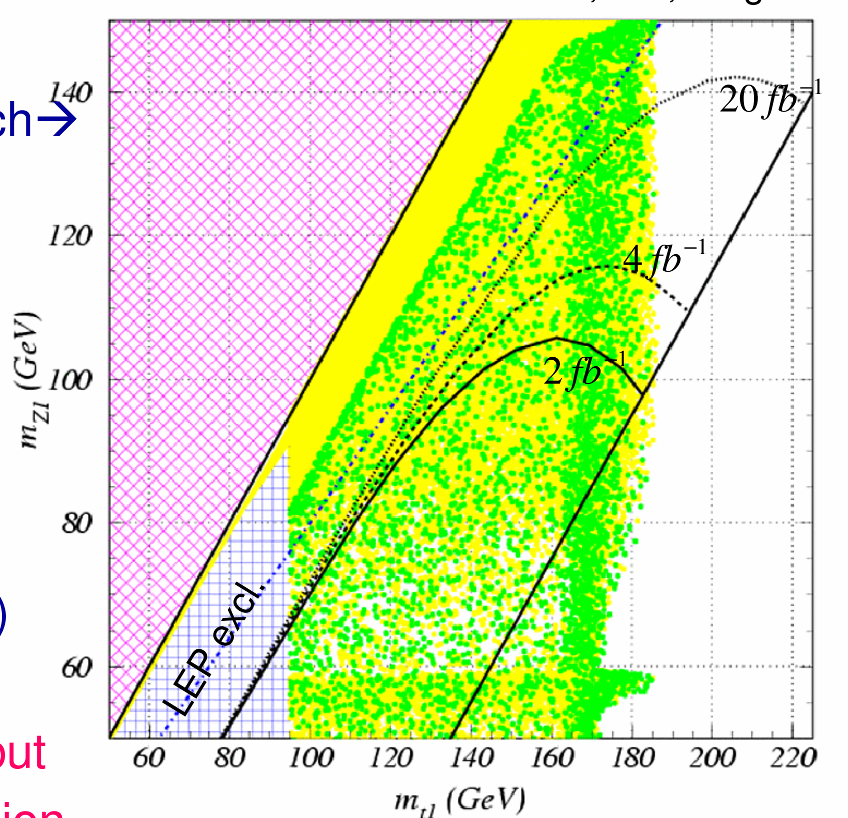
- if $\tilde{t} \longrightarrow c\tilde{\chi}$ decay mode dominant and $\Delta_{m_{\tilde{t}\tilde{\chi}}}$ < 30 GeV:

  trigger on $\not{E}_T$ crucial

$$m_{\tilde{\chi}^0} < 100\,\mathrm{GeV}\ \text{and}\ m_{\tilde{t}} \leq 180\,\mathrm{GeV}\ \text{at reach if}\ \Delta_{m_{\tilde{t}\tilde{\chi}}} \geq 30\,\mathrm{GeV}$$

$$m_{\tilde{\chi}^0} \geq 120\,\mathrm{GeV}\ \text{then}\ m_{\tilde{t}}\ \text{out of reach}$$

MSSM Balazs, MC, Wagner'04



- co-annihilation region not at Tevatron reach→
- away from it strong dependence on the neutralino mass

- if $m_{\tilde{t}} > m_{\tilde{\chi}} + m_W + m_b$ (3-body decay)

this always happens for

(h-resonance) $m_{\tilde{\chi}^0} \approx m_h / 2$

and $m_{\tilde{t}} \geq 140\,\mathrm{GeV}$ no reach

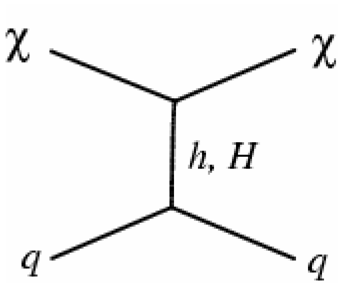
(can search for charginos in trilepton channel)

LHC: good for chargino/neutralino searches but also difficulties for stops in co-annihilation region

Direct Dark Matter Detection

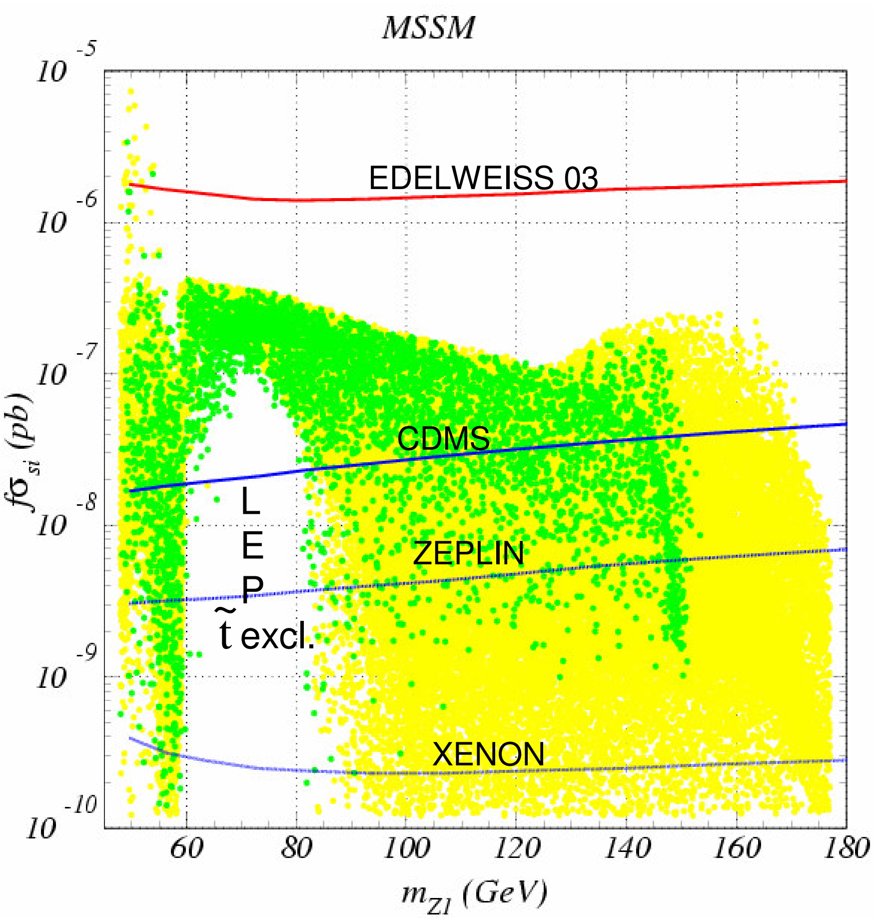
$\not{E}_T$ at colliders → important evidence of DM candidate,
but, stability of LSP on DM time scales cannot be chekced at colliders

Neutralino DM is searched for in neutralino-nucleon scattering exp. detecting elastic recoil off nuclei



→ upper bounds on Spin independent cross sections

Next few years: $\sigma_{SI} \approx 10^{-8}\,\mathrm{pb}$
Ultimate goal: $\sigma_{SI} \approx 10^{-10}\,\mathrm{pb}$ (Fiorucci's talk)



small σ_{si} for large μ : co-annihilation and h-resonant regions

Balazs, MC, Wagner '04

Conclusions

- **Supersymmetry with a light stop** $m_{stop} < m_{top}$ **and a SM-like Higgs with** $m_h < 120\ \text{GeV}$

$\downarrow$

opens the window for electroweak baryogenesis and allows for a new region of SUSY parameter space compatible with Dark Matter

also Gaugino and higssino masses of order of the electroweak scale and moderate CP-odd Higgs mass preferred

EWBG and DM in the MSSM → interesting experimental framework

stop-neutralino co-annihilation → challenging for hadron colliders

Tevatron: good prospects in searching for a light stop

LHC: will add to these searches and explore the relevant $\tilde{\chi}^0$ / $\tilde{\chi}^{\pm}$ spectra

Stop co-annihilation region provides motivation to search in the small $\Delta_{m_{\tilde{t}\tilde{\chi}}}$ regime

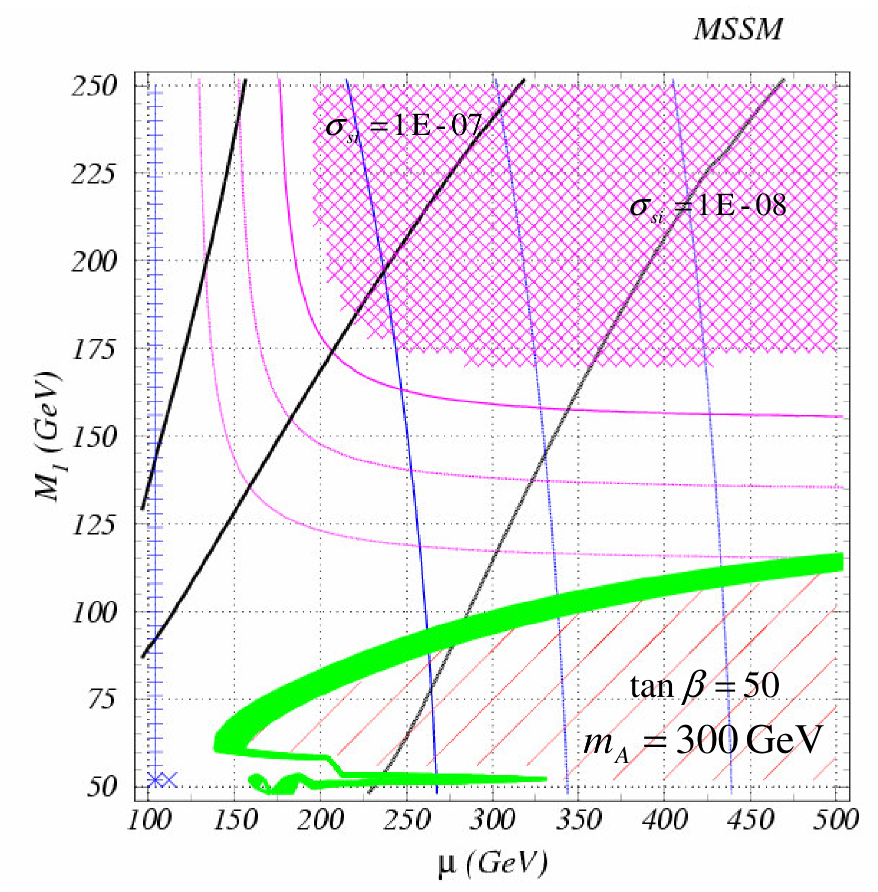
LC: important role in testing this scenario: small $\Delta_{m_{\tilde{t}\tilde{\chi}}}$ and nature and composition of light gauginos and stop

Direct Dark Matter detection: nicely complementary to collider searches

$\tan\beta$ Effects on the neutralino relic density

Main effect is via the coupling of the heavy Higgs A,H to bottom quarks

- annihilation cross section grows quadratically with $\tan\beta$



- For sufficiently small heavy Higgs masses and large tan beta:

$m_A \approx 250 -\!- 300\,\text{GeV}$ $\quad\tan\beta \approx 50$

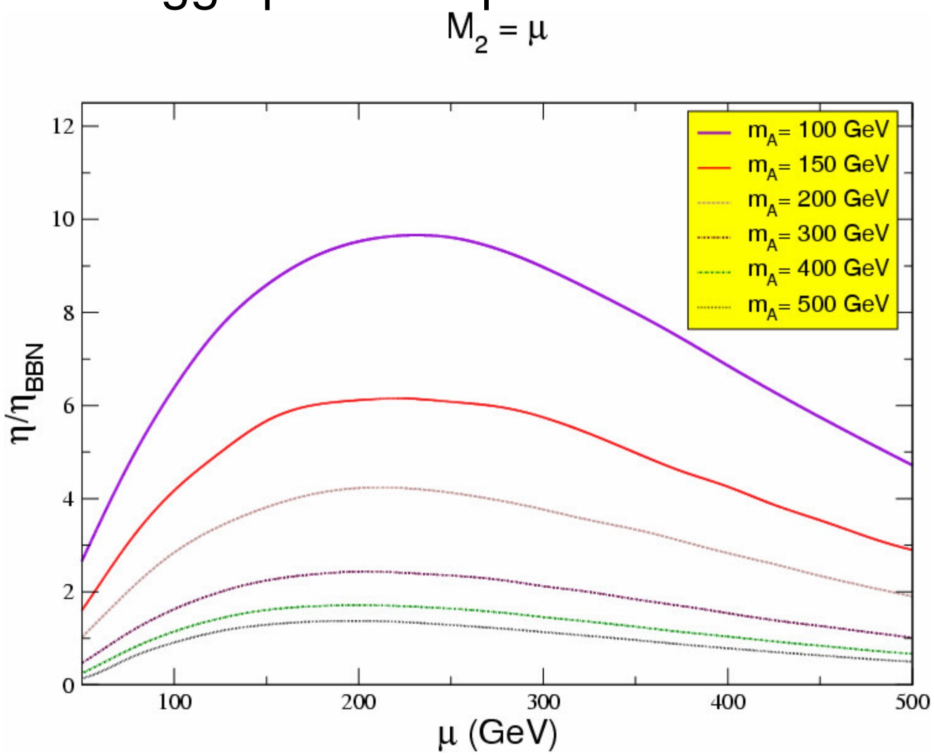
can have dramatic cosequences on the allowed region of parameter space

($m_A \approx 200\,\text{GeV}$ can make the relic density too small over most of the space)

Balazs, MC, Wagner

• New sources of CP violation from the sfermion sector

- Generation of the baryon asymmetry: Charginos with masses μ and M_2 play most relevant role.
- CP-violating Sources depend on $\arg(\mu^* M_2)$
- Higgs profile depends on the mass of the heavy Higgs bosons .



We plot for maximal mixing: within uncertainties, values of $\sin\phi_\mu \leq 0.05$ preferred

Gaugino and Higgsino masses of the order of the weak scale highly preferred

Large CP-odd Higgs mass values are acceptable

M.C., Quiros,. Seco and Wagner '02

Additional Topics

Conclusions

- Supersymmetry may play a relevant role in the origin of particle masses, is consistent with unification and provides a dark matter candidate.

- It may also be essential in the generation of the baryon asymmetry if

  $m_H < 120 \ \mathrm{GeV}$ and $m_{stop} < m_{top}$

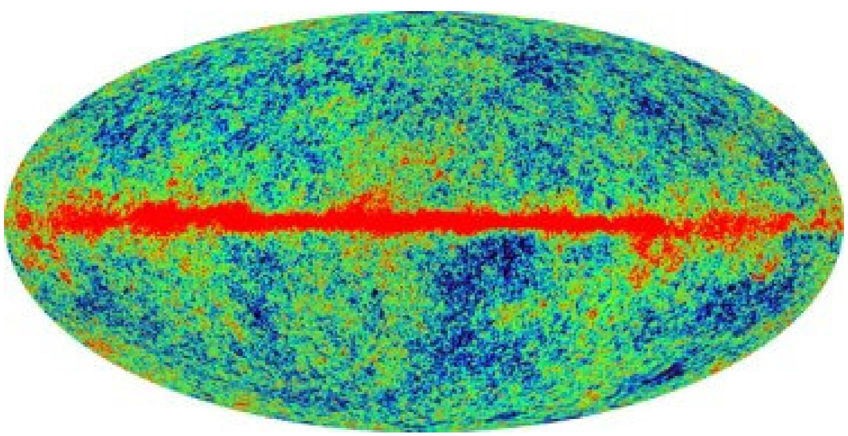
- Tevatron and LHC colliders will probe soon the realization of this scenario.

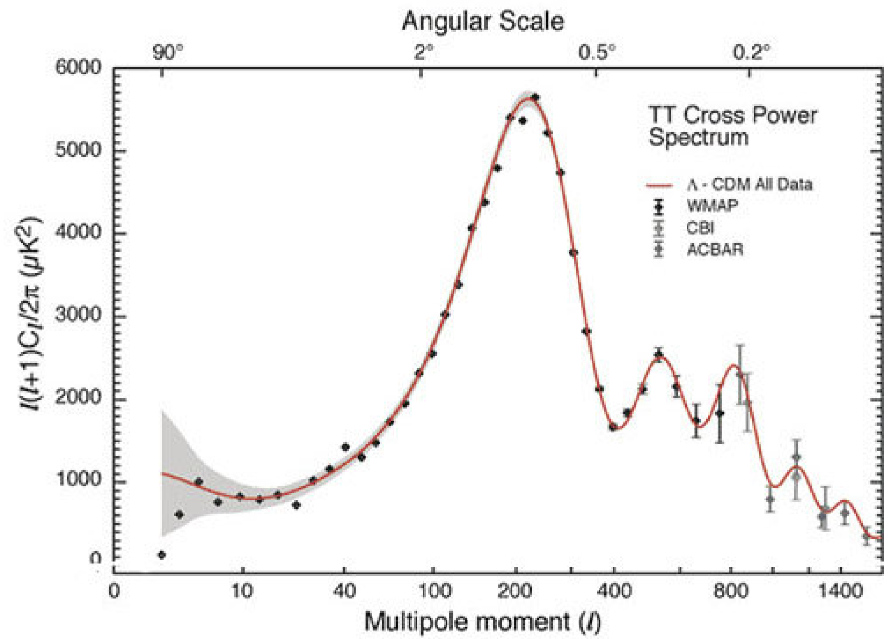
Cosmic Microwave Background

WMAP measures the CMB and studies correlations at very small scales.
In agreement with Sloan Digital Sky Survey determined :

$\Omega_M h^2 = 0.135 \pm 0.009$ $\Omega_B h^2 = 0.0224 \pm 0.0009$ $h = 0.71 \pm 0.04$

difference gives CDM energy density: $\Omega_{\mathrm{CDM}}\ \mathrm{h}^2 = 0.1126 \pm^{0.0161}_{0.0181}$





Possible origin of Dark Matter

- Weakly interacting particles (WIMPS), with masses and interaction cross sections of order of the electroweak scale

  $\longrightarrow$ most compelling alternative

- Supersymmetry, with R parity conservation

naturally provides a stable, neutral, dark matter candidate: $\tilde{\chi}^0$

Relic Density

- **To estimate $\tilde{\chi}^0$ relic density, assume it was in thermal equilibrium in the early universe:** $n_{eq} = g\left(\frac{mT}{2\pi}\right)^{3/2} Exp[-m/T]$

- Interactions with the relativistic plasma are efficient, but the WIMPs follow a Maxwell-Boltzmann distribution.

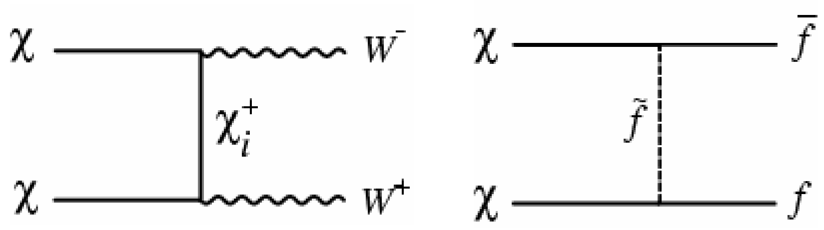
However, the universe is expanding, and once the density is small enough, they can no longer interact with one another, and fall out of equilibrium.

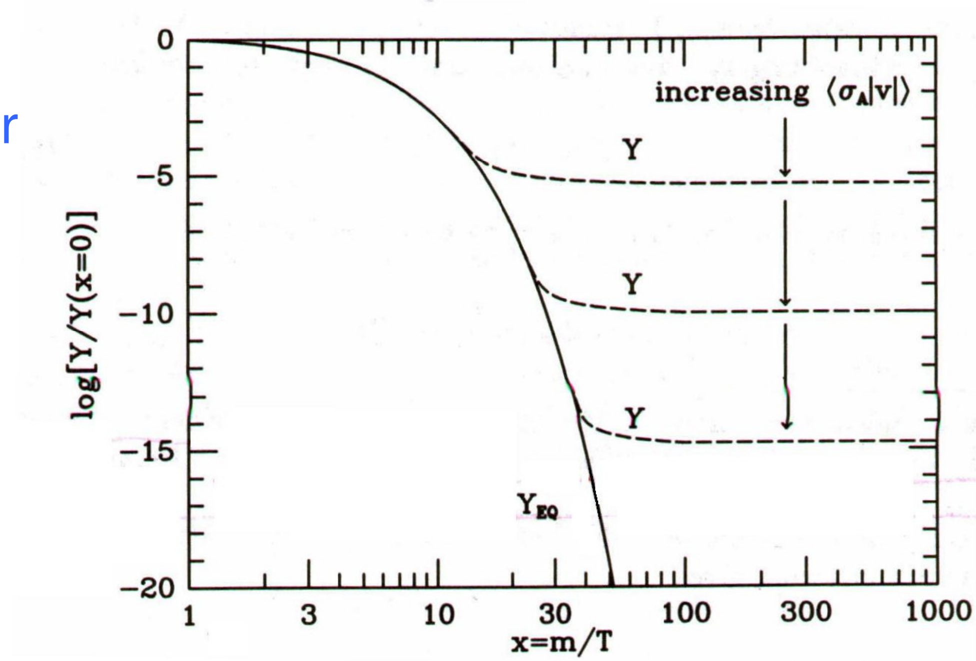
- Below the freeze–out temperature, the WIMPs density per co-moving volume is fixed

$$\frac{dY}{dx} = -\frac{\langle \sigma \, v \rangle}{H\, x} s \left(Y^2 - Y_{eq}^2 \right) \qquad \text{with } Y = n/s \text{ and } x = m/T$$

The key ingredient is the thermally averaged annihilation cross section $\langle \sigma \, v \rangle$

- Computing $\tilde{\chi}^0 \tilde{\chi}^0$ annihilation cross section yields the dark matter relic density





If any other SUSY particle has mass close to the neutralino LSP, it may substantially affect the relic density via co-annihilation

In Supersymmetry both problems can be solved

- EW Baryogenesis requires new boson degrees of freedom with strong couplings to the Higgs.

- Relevant SUSY particle: Two Superpartners of the top, one for each chirality (left and right).

  Each stop has six degrees of freedom (3 of color, 2 of charge) and coupling of order one to the Higgs

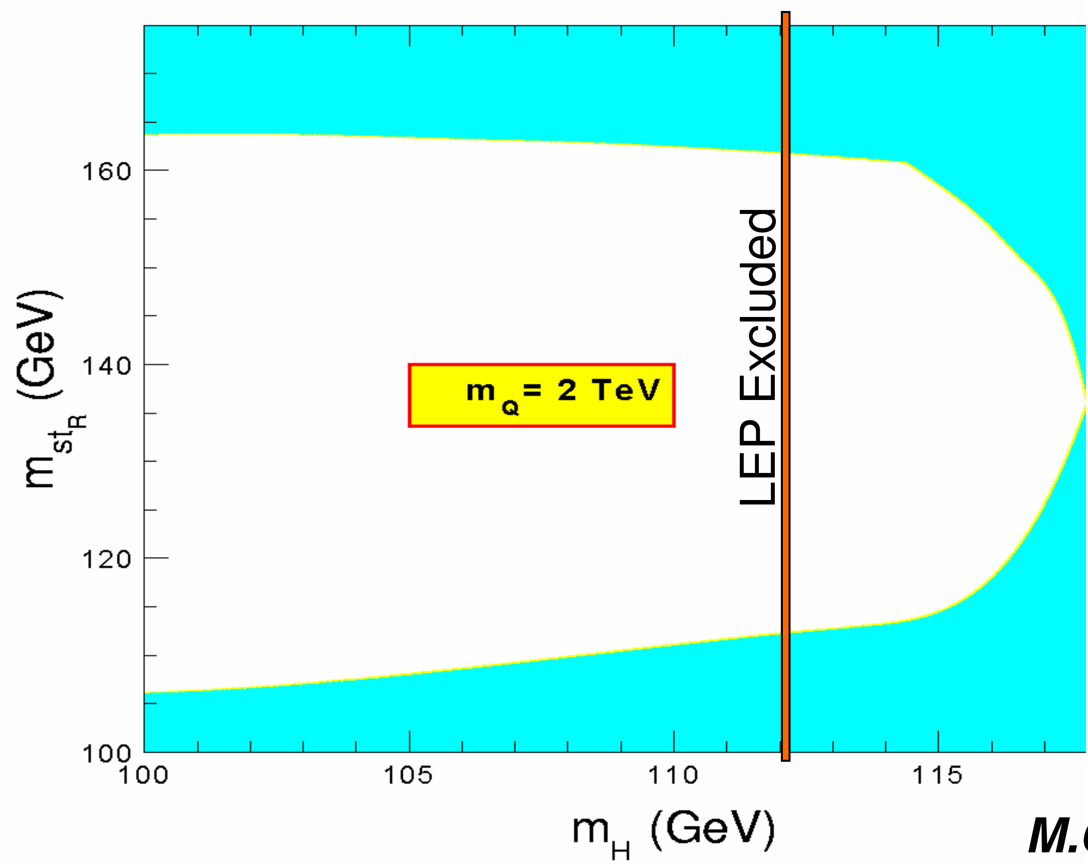
$$E_{SUSY} = \frac{g_w^3}{4\pi} + \frac{h_t^3}{2\pi} \approx 8\, E_{SM} \qquad \text{since} \quad \frac{\mathrm{v}(T_c)}{T_c} \approx \frac{E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{\mathrm{v}^2}$$

One of the stops has to be light, to induce a strong first order phase transition. The other needs to be heavier than about 1 TeV in order to make the Higgs mass larger than the current bound

Upper bound on the Higgs imposed by the requirement of the preservation of the baryon asymmetry.

Limits on the Stop and Higgs Masses to preserve the baryon asymmetry

- ***Higgs masses up to 120 GeV may be accomodated***
- ***The lightest stop must have a mass below the top quark mass.***



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Generation of the Baryon Asymmetry

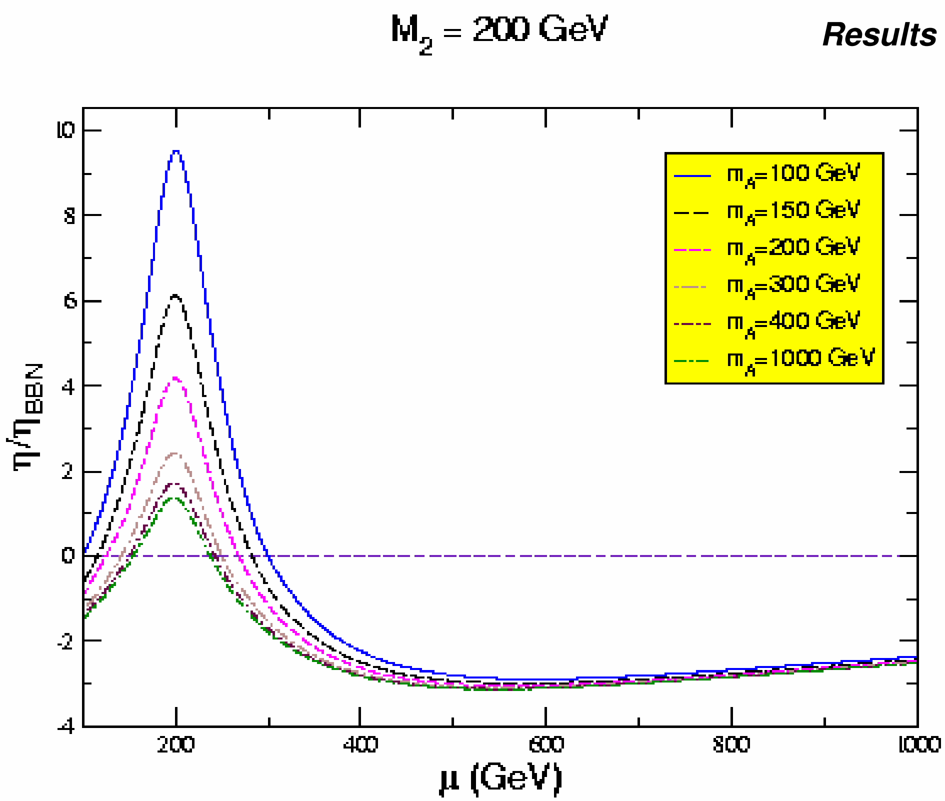
- Superpartners of the Higgs and SU(2) gauge boson, with masses μ and M2 (charginos), play most relevant role.

- Baryon charge generated in walls of bubbles expanding at the time of the first order electroweak phase transition.

- CP-violating Sources depend on $\arg(\mu^* M_2)$
- also on the bubble wall Higgs profile.

- Higgs profile depends on the mass of the heavy Higgs bosons m_A.

Baryon Asymmetry Dependence on the Chargino Mass Parameters



Results for maximal CP violation

Gaugino and Higgsino masses of the order of the weak scale highly preferred

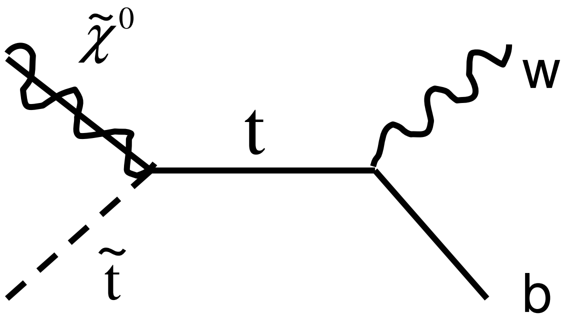
M.Carena, M.Quiros, M. Seco and C.W. '02

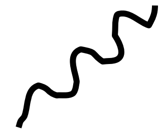
Baryon Asymmetry Enhanced for $M_2 = |\mu|$

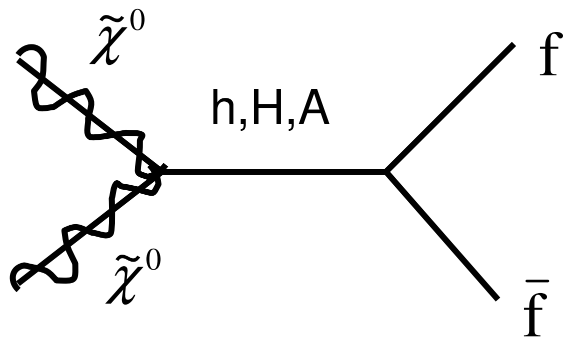
Even for large values of the CP-odd Higgs mass, acceptable values obtained for phases of order one.

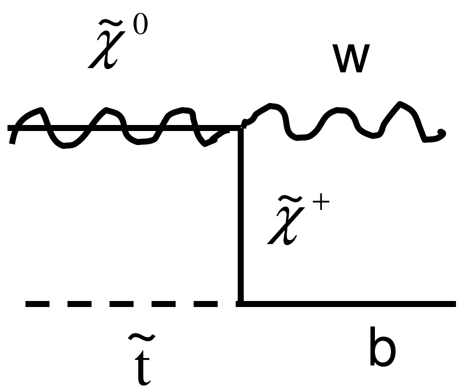
Stop Signatures

- Light Stop can decay into the lighter charginos or neutralinos.
- Stop signatures depend on this and also on the mechanism of supersymmetry breaking.
- In standard scenarios, where neutralino is the dark matter, stop may decay into a light up-quark and a neutralino: Two jets and missing energy.
- In models in which supersymmetry is broken at low energies, the neutralino may decay into a photon and a gravitino, the superpartner of the graviton.

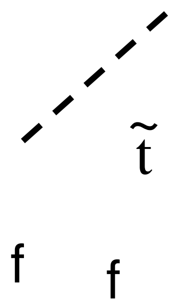




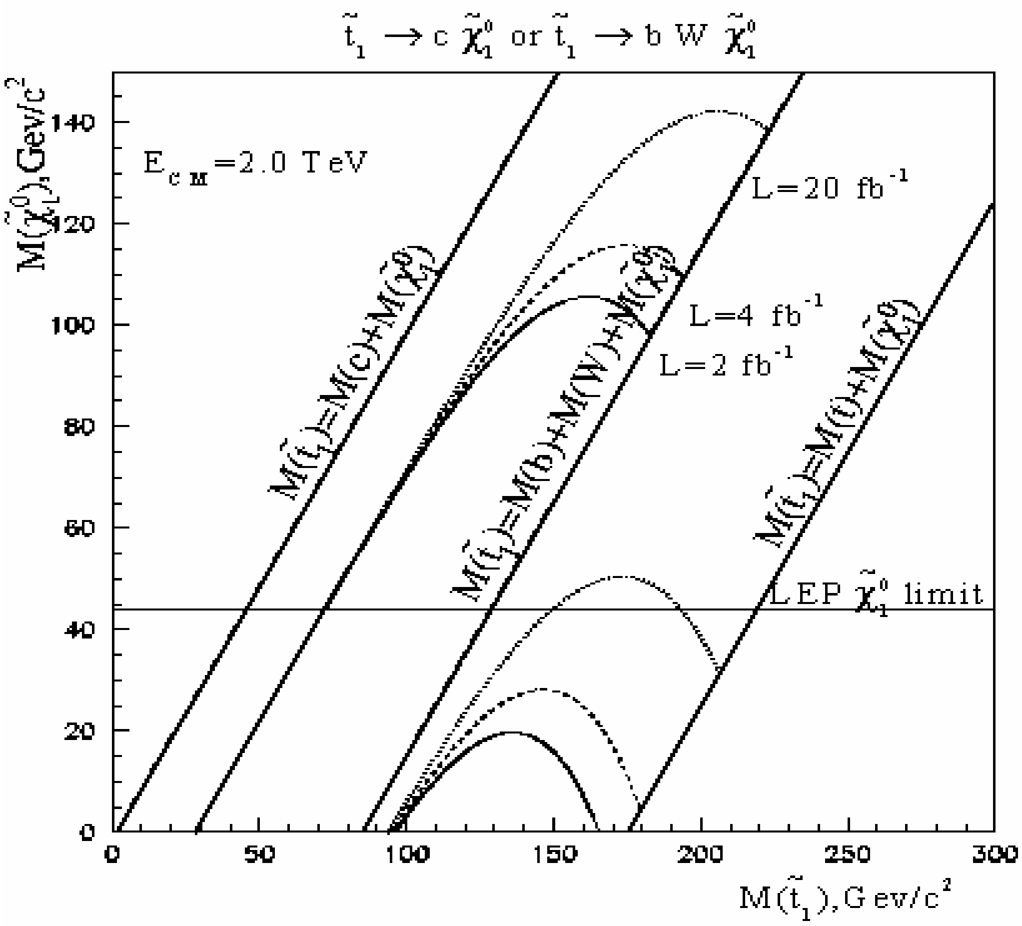




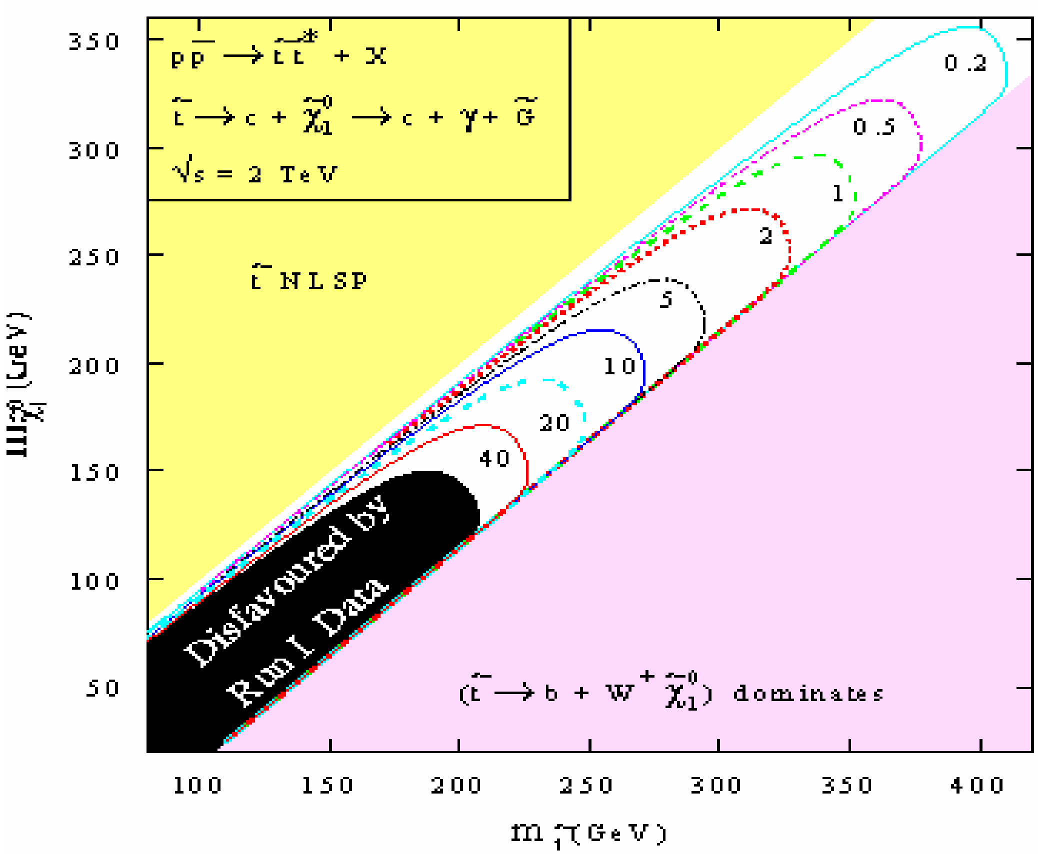
$m_A = 2\, m_{\tilde{\chi}}$ the $\tilde{t} - \tilde{\chi}$



Stop Signatures at the Tevatron
Neutralino as Dark Matter



Stop Searches at the Tevatron
Neutralino decaying into photons



Anomalies arise in the process of regularization of divergences. Impossible to do it preserving gauge and B and L symmetries.

$$\partial^{\mu} j_{\mu}^{B,L} = \frac{N_g}{32\,\pi^2} Tr(\;\varepsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta}\;)$$

Instantons are minimal action configuration with non-vanishing values of the integral of the right –hand side of the above Eq.

Instanton configurations may be regarded as semiclasical amplitudes for tunelling effect between vacuum states with different baryon number

$$S_{inst} = \frac{2\pi}{\alpha_W} \qquad\qquad \Gamma_{\Delta B \neq 0} \propto \exp(-S_{inst}\;)$$

Weak interactions: Transition amplitude exponentially small. No observable baryon number violating effects at T = 0

Washout of Baryon Asymmetry

- *Baryon Number violated in the SM* at high temperatures.

- B-L, instead, is preserved by anomalous processes

$$\Delta B = \Delta L = N_g \quad \Rightarrow \quad \Delta(B\text{-}L) = 0$$

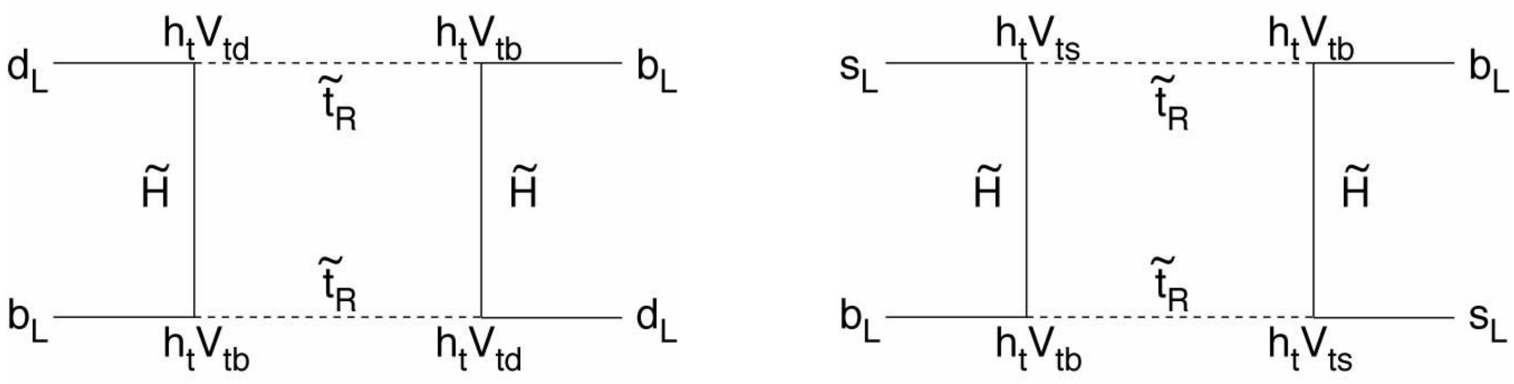
- If, original asymmetry had B = L, final asymmetry : B = L = 0.

- For successful generation of B asymmetry, decay of heavy particles should lead to

$$B - L \neq 0$$

Other Signals

– 20% enhancements to Δm_d, Δm_s with the same phase as in the SM (Murayama, Pierce)



- Large phases in the chargino sector may induce large electric dipole moments for quarks and leptons: They lead to a bound on the first and second generation sfermions masses of about 2 TeV (Pilaftsis, Carena,Quiros,Seco and C.W.)

Why Supersymmetry ?

- Helps to stabilize the weak scale—Planck scale hierarchy

- Supersymmetry algebra contains the generator of space-time translations.
  Necessary ingredient of theory of quantum gravity.

- Minimal supersymmetric extension of the SM :
  Leads to Unification of gauge couplings.

- Starting from positive masses at high energies, electroweak symmetry breaking is induced radiatively.

- If discrete symmetry, $P = (-1)^{3B+L+2S}$ is imposed, lightest SUSY particle neutral and stable: Excellent candidate for cold Dark Matter.

Generation Process

- Interaction with Higgs background creates a net chargino excess through CP-violating interactions
- Chargino interaction with plasma creates an excess of left-handed anti-baryons (right-handed baryons).
- Left-handed baryon asymmetry partially converted to lepton asymmetry via anomalous processes
- Remaining baryon asymmetry diffuses into broken phase
- Diffusion equations describing these processes derived

Upper Bound on the Lightest Higgs Mass (minimal SUSY)

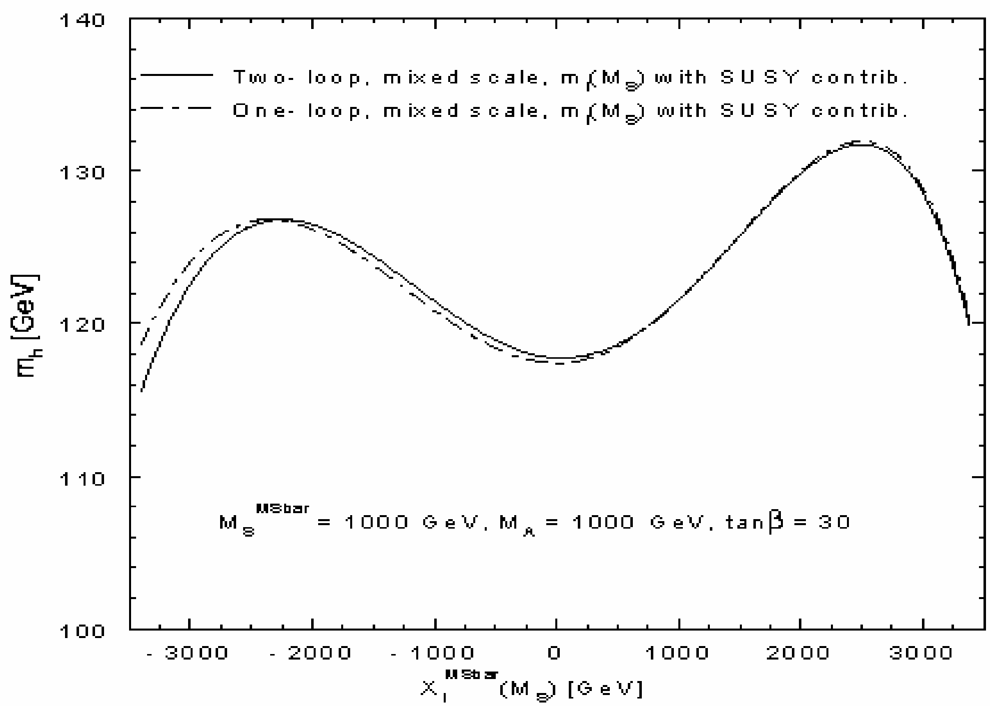
Supersymmetry requires two Higgs doublets. Two CP-even and one CP-odd neutral Higgs bosons.

$$< H_2 > = v_2 \quad , \quad < H_1 > = v_1$$

M_s= Mass of the top-quark superpartner

M_A = Mass of the heavy neutral Higgs bosons

X_t = Left-right Stop mixing parameter



Lightest Higgs boson mass smaller than 135 GeV.

M. Carena, M. Quiros, C.W. (1996); with Haber et al. (2000)

Problems in the Standard Model

- A more careful examination shows that, in the SM, phase transition is a cross over for any value of the Higgs mass.

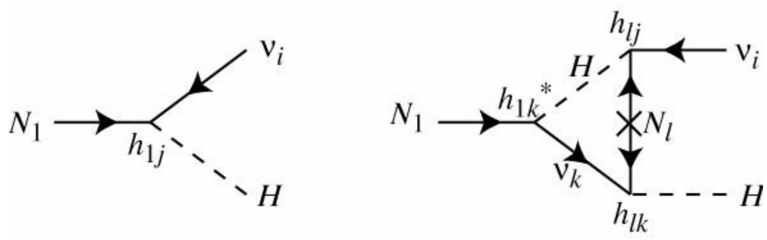
- Second, independent problem: Not enough CP violation. In the SM, this is measured by

$$\det[M_u^+ M_u, M_d^+ M_d] / T_c^{12} \approx 10^{-20}$$

- Both problems solved with Supersymmetry:
  Phase Transition strongly first order
  New CP violating phases

Leptogenesis

- Heavy, right-handed neutrinos decay out-of-equilibrium



- CP violating phases appear in the interference between the tree-level and one-loop amplitudes.

- Majorana fermions have extra physical phases. Two generations of neutrinos would be sufficient for the mechanism to work

- *Detailed calculation shows that lightest right handed neutrino mass should be* $M_1 \sim 10^{10}$ GeV to obtain proper baryon asymmetry.

- Leptogenesis may work even in the absence of supersymmetry. (In SUSY reheating temperatures of the order of dangerous, since they lead to overproduction of gravitinos).

Higgs Physics and Supersymmetry

- Quartic couplings of the Higgs boson governed by the gauge couplings.

- At tree level, the lightest Higgs boson mass is smaller than Mz (91 GeV).

- Prediction modified by radiative corrections induced by supersymmetry breaking effects.

- Most relevant particle : Superpartner of the top-quark (large coupling to the Higgs).

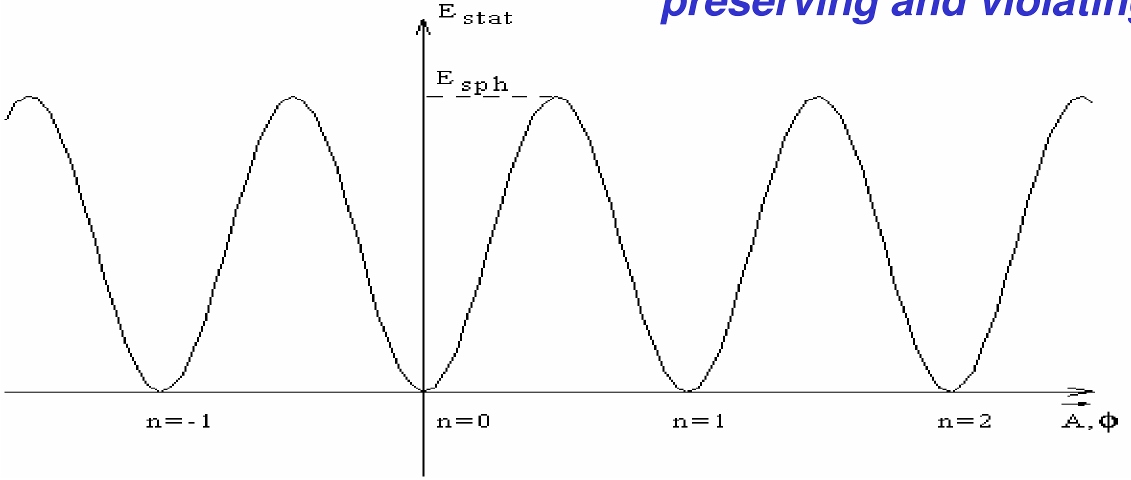
Non-equivalent Vacua and Static Energy in Field Configuration Space

Vacua carry different baryon number.
The sphaleron is a static configuration with non-vanishing values of the Higgs and gauge boson fields.

Its energy may be identified with the height of the barrier separating vacua with different baryon number

$$E_{sph} = \frac{8\pi \, \mathrm{v}}{g_W}$$

The quantity v is the Higgs vacuum expectation value, $\langle H \rangle = v$.
This quantity provides an order parameter which distinguishes the electroweak symmetry preserving and violating phases.



Relevant masses and Phases

- The chargino mass matrix contains new CP violating phases

$$\begin{pmatrix} M_2 & \sqrt{2} m_W \cos\beta \\ \sqrt{2} m_W \sin\beta & \mu \end{pmatrix}$$

- Some of the phases may be absorbed in field redefinition. For real Higgs v.e.v.'s, the phase

$$\arg(\mu^* M_2)$$

  is physical

- Sources depend on the Higgs profile. They vanish for large values of

$$\tan\beta = \frac{v_2}{v_1}$$

Heavy Particle Decay with $B - L \neq 0$

- Idea : Generate a non-vanishing lepton number at high energies.

- Baryon number generated from lepton number plus anomaly interactions, which convert L to B: Leptogenesis (Fukugita, Yanagida)

- Makes use of standard explanation of small neutrino masses.

- Relies in the presence of heavy Majorana neutrinos

- *Detailed calculation shows that lightest right handed neutrino mass should be* $M_M \sim 10^{10}$ GeV to obtain proper baryon asymmetry.

Baryogenesis by Decay of Heavy Particles

- First simple models of baryogenesis proposed in the context of Grand Unified Models.

- A heavy GUT-scale particle *X* decays out-of-equilibrium with direct CP violation

$$B(X \rightarrow q) \neq B(\overline{X} \rightarrow \overline{q})$$

Neutrino Masses: Seesaw Mechanism

- Neutrino Masses much smaller than charged fermion ones
- Explanation: Neutrinos are Majorana particles. Dirac mass equal in size to charged particle masses.
- Large right handed mass. Mass matrix in base

$$(\nu_L, \nu_R) \qquad \begin{bmatrix} 0 & \mathrm{m_D} \\ \mathrm{m_D^T} & \mathrm{M} \end{bmatrix}$$

- Small mass eigenvalue, consistent with experiment if M is very large

$$\mathrm{m}_i = \frac{\mathrm{m}_{\mathrm{D_i}}^2}{\mathrm{M_i}} \qquad \left(\mathrm{m} = \mathrm{m_D}\,\mathrm{M}^{-1}\mathrm{m_D^T}\right)$$